A 72-μW 90-dB Wide-Range Potentiostatic CMOS $\Delta\Sigma$ Modulator with Flicker Noise Cancellation for Smart Electrochemical Sensors

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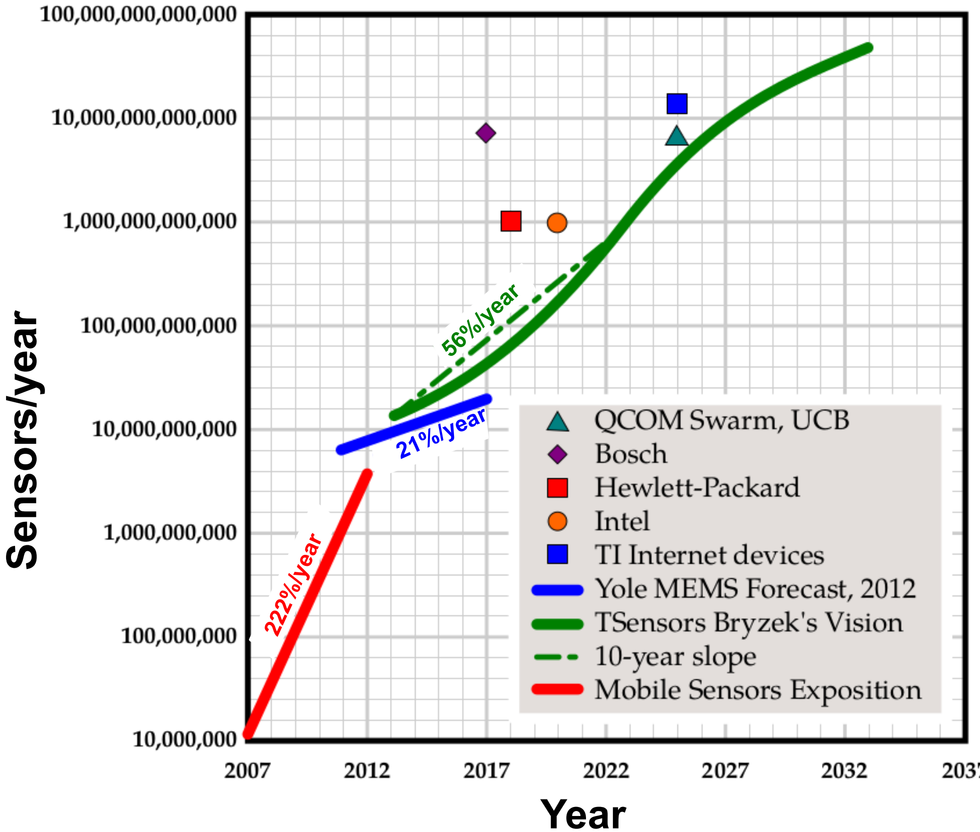
Sensors Maket Vision

- Several organizations created visions for continued growth to trillion(s) sensors
  - $15 trillion by 2022
- **Electrochemical sensors** are growing exponentially due to potential of miniaturization and mass production
  - **Monolithic** or **hybrid** integration onto CMOS platforms
  - Applications in biosensors, quality control, health care, ...



Expected sensor production growth per year

www.eenewsanalog.com

1 Amperometric Electrochemical Sensors

2 Potentiostatic $\Delta\Sigma$ Modulator architecture

3 Proposed wide-range potentiostat with 1/f noise cancellation

4 0.18-μm CMOS Design and Post-Layout simulations

5 Conclusions

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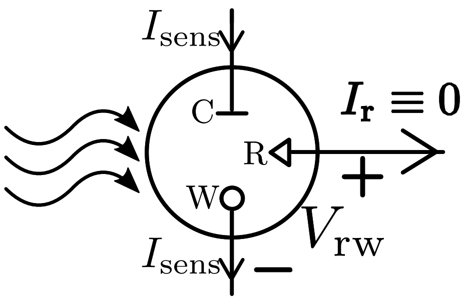
Amperometric Electrochemical Sensors

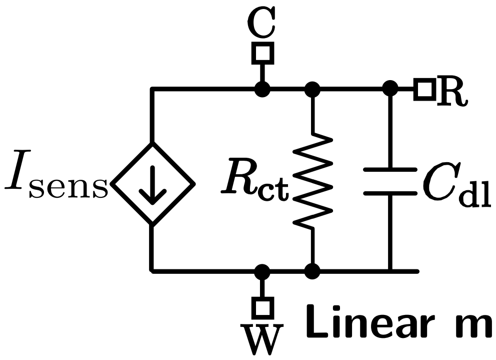
- ▲ Interaction with microorganisms.
- ▲ **Selectivity** by functionalization.

- ▼ Reduced **speed** and **life** time.
- ▼ **Potentiostatic** and **amperometric** operations.



- ▶ **Three electrodes:**
  - **W**orking
  - **R**eference
  - **C**ounter
- ▶ Measurement independent of the **R** and **C** impedances.
- ▶ Current associated to the electrons involved in a **redox** process:

$$0 + e^- \underset{\text{ox}}{\overset{\text{red}}{\rightleftharpoons}} R$$



- Electrochemical **time constant:**

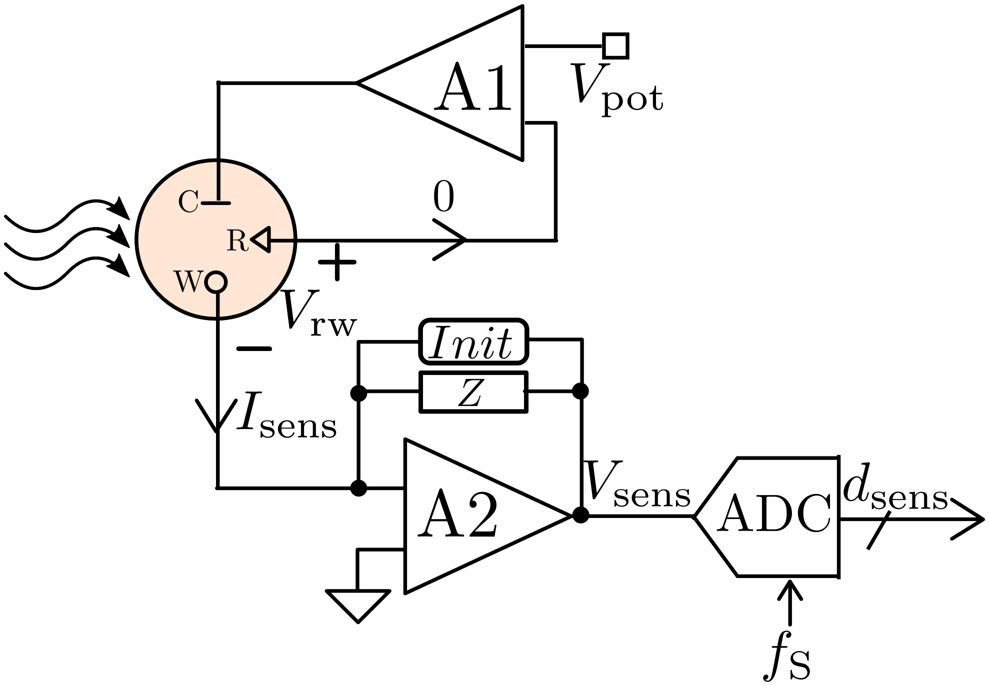
$$\tau_{\text{ch}} = R_{\text{ct}} C_{\text{dl}} \approx 10^{-1}\text{s}$$

Classic circuit implementation

- **Potentiostat**
  - A_1 establishes the control loop to accomplish potentiostat operation.

    $$V_{rw} = V_{pot} \quad \& \quad I_r \equiv 0$$

- **Amperometry**
  - A_2 converts sensor current to voltage for digitization and readout.



- Requires **multiples OpAmps + ADC.**
- Large **area** and **power consumption.**

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1st order Potentiostatic $\Delta\Sigma$M

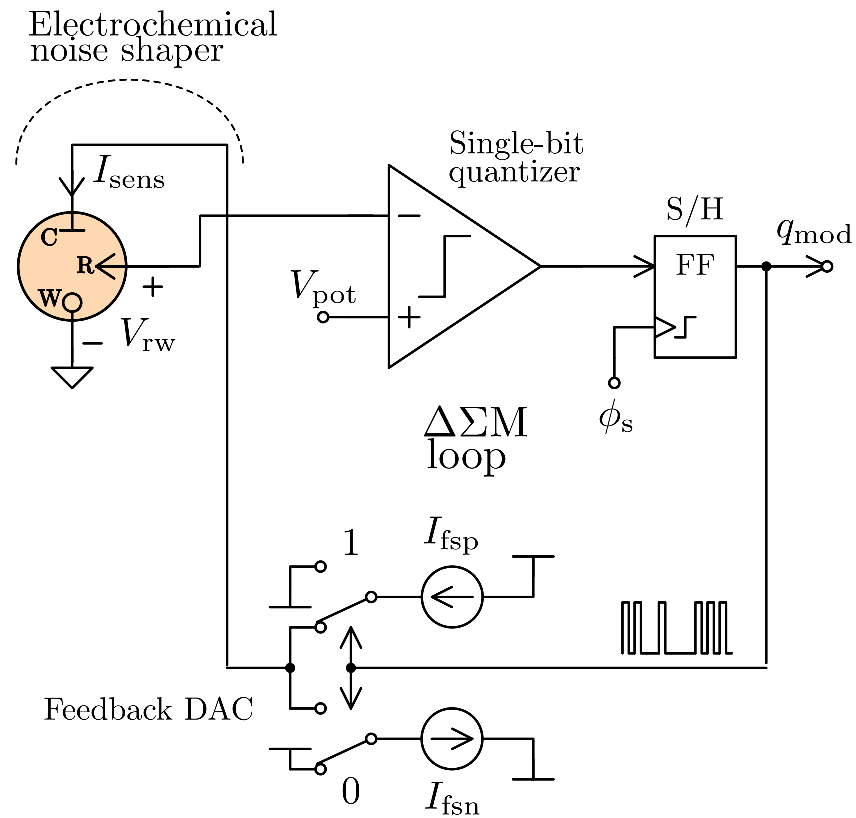
- *Sensor-on-the-loop*

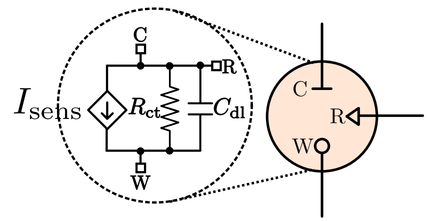
  Behaviour similar to **low-pass first-order single-bit CT** $\Sigma\Delta$M A/D modulator.

- Error current converted into voltage and shaped in frequency by the **electrochemical sensor** itself.

- High **OSR** easily obtained with kHz-range clock frequencies.

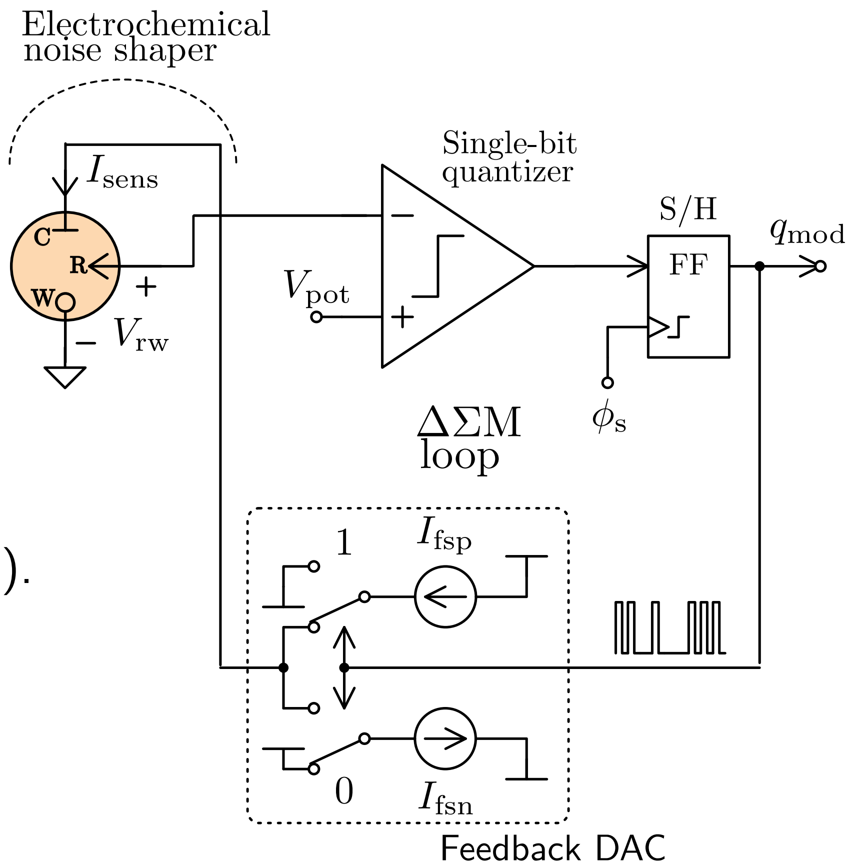
- **Amperometric** read-out through the $\Sigma\Delta$M output q_{mod} by chemical input I_{sens}.





Linear model

1^{st} order Potentiostatic $\Delta\Sigma M$



- Typical **tonal component** of 1^{st} order $\Delta\Sigma M$
- Limited **potentiostatic range programmability** (Vrw):
  Vpot only applies to the Reference Electrode (R).
- **DAC flicker noise** not shaped by $\Delta\Sigma$ loop.
  Noise floor in the signal band (BW $<$ 1Hz) dominated by flicker noise.

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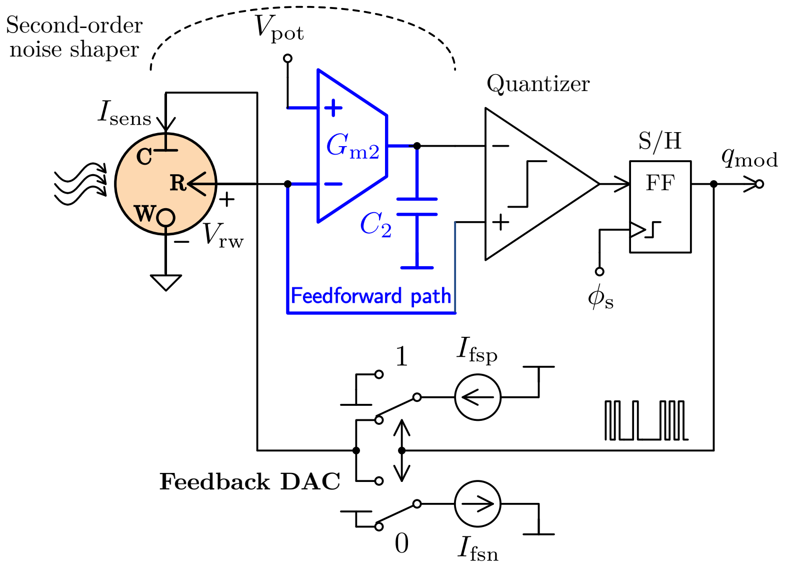
From 1st to 2nd order $\Delta\Sigma$M

- From electrochemical only $\mathcal{T}$ to **hybrid/mixed electrochemical/electronic** $\mathcal{T}_S$
- **Tones** and pattern noise **suppression.**



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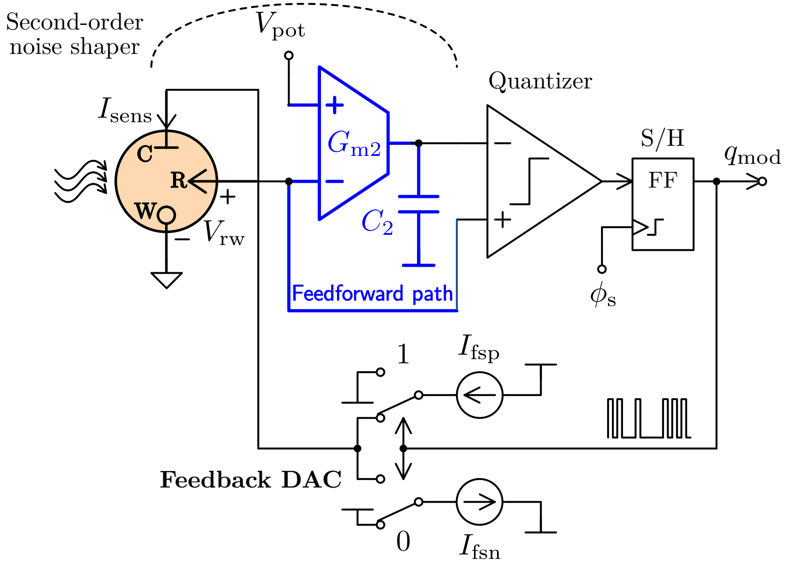
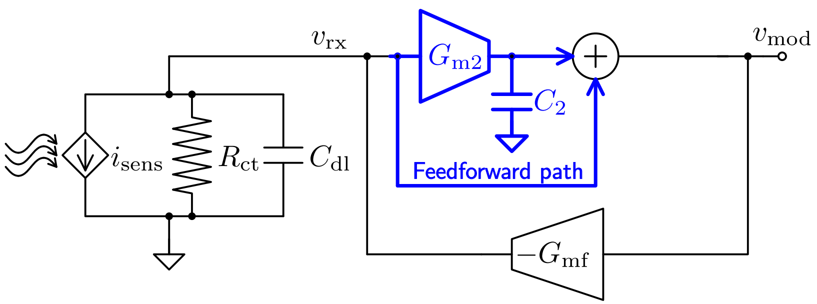


- Small-signal model



$$L_1(s) = -R_{ct}G_{mf}\frac{1+\tau_2 s}{(1+\tau_1 s)\,\tau_2 s}$$

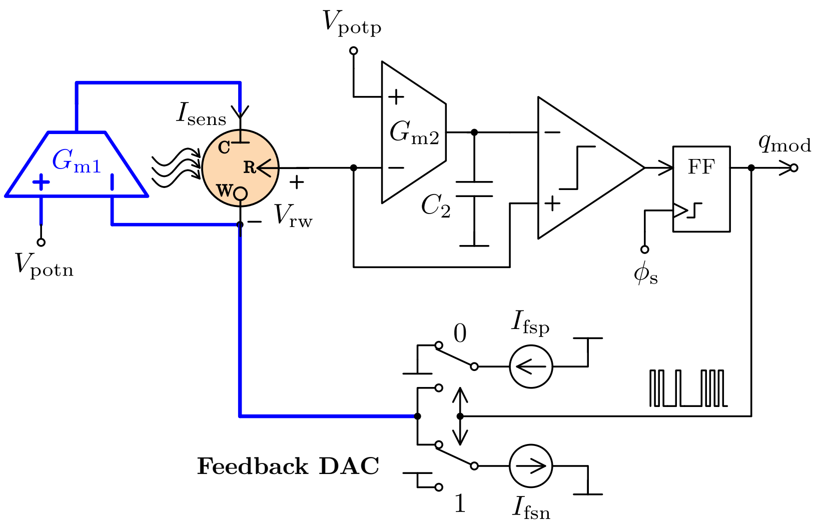
$$\tau_1 \doteq R_{ct}C_{dl} \qquad \tau_2 \doteq \frac{C_2}{G_{m2}}$$

- 2^{nd} order $\Delta\Sigma M$ requires **stability compensation**
  - LHP Zero through feedforward path

Wide-range potentiostatic 2nd order ΔΣM

- **Programmable-WE** through Gm_1:
  - Extend potentiostatic range virtually up to **double the supply voltage:**

$$V_{\mathrm{rw}} = V_{\mathrm{potp}} - V_{\mathrm{potn}}$$



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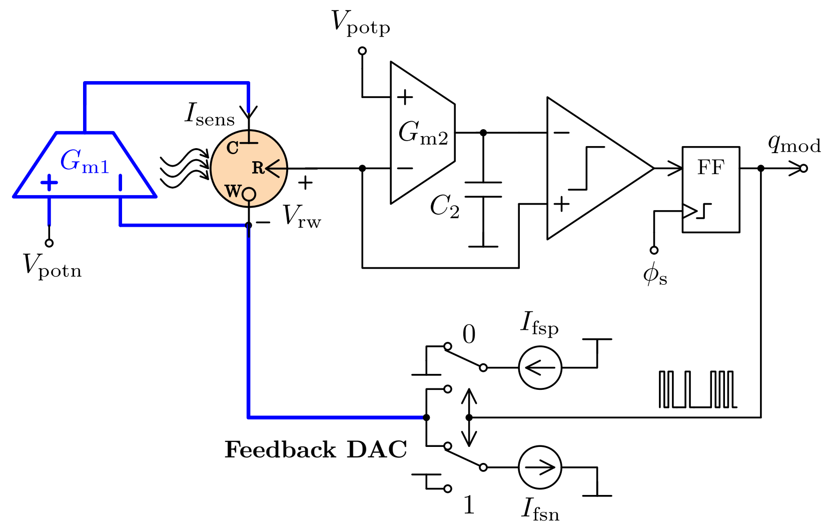

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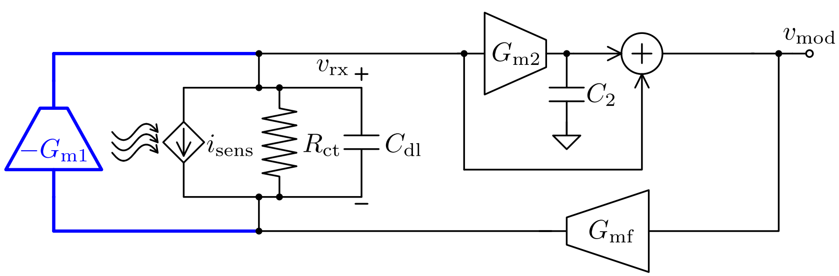

$$L_2(s) = -G_{\mathrm{mf}}\left(\frac{G_{\mathrm{m1}}R_{\mathrm{ct}} - 1}{G_{\mathrm{m1}}}\right)\frac{1 - \frac{\tau_1}{G_{\mathrm{m1}}R_{\mathrm{ct}}-1}s}{1+\tau_1 s}\frac{1+\tau_2 s}{\tau_2 s}$$

- Loop stability:
  - **High power consumption on Gm_1** to push RHP zero to high frequencies:
    - $G_{\mathrm{m1}} \gg \frac{1}{R_{\mathrm{ct}}}$

$$L_2(s) = L_1(s) = -R_{\mathrm{ct}}G_{\mathrm{mf}}\frac{1+\tau_2 s}{(1+\tau_1 s)\,\tau_2 s}$$

Differential DAC wide-range potentiostatic 2[nd] order ΔΣM

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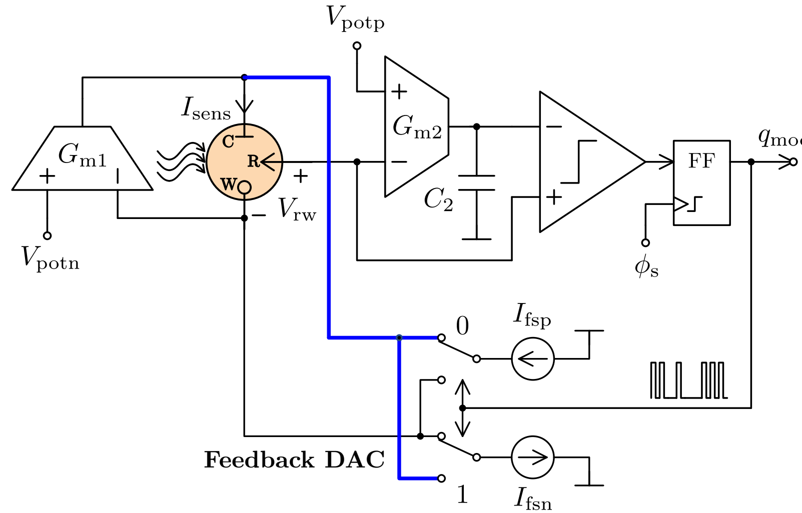

Differential DAC wide-range potentiostatic 2nd order ΔΣM

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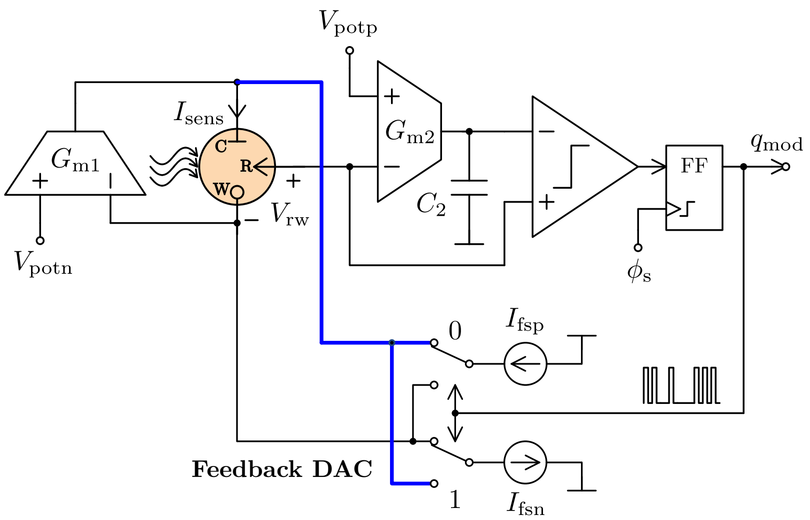

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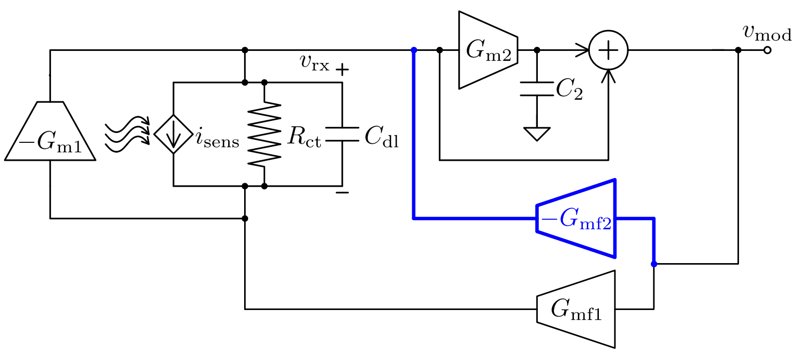


$$L_3(s) = -G_{\mathrm{mf1}}\left(\frac{R_{\mathrm{ct}}}{1+\tau_1 s} - \frac{1-\frac{G_{\mathrm{mf2}}}{G_{\mathrm{mf1}}}}{G_{\mathrm{m1}}}\right)\frac{1+\tau_2 s}{\tau_2 s}$$

- Loop stability:
  - **RHP self-canceled**
    both Ifsp,n are used in both quantization symbols.

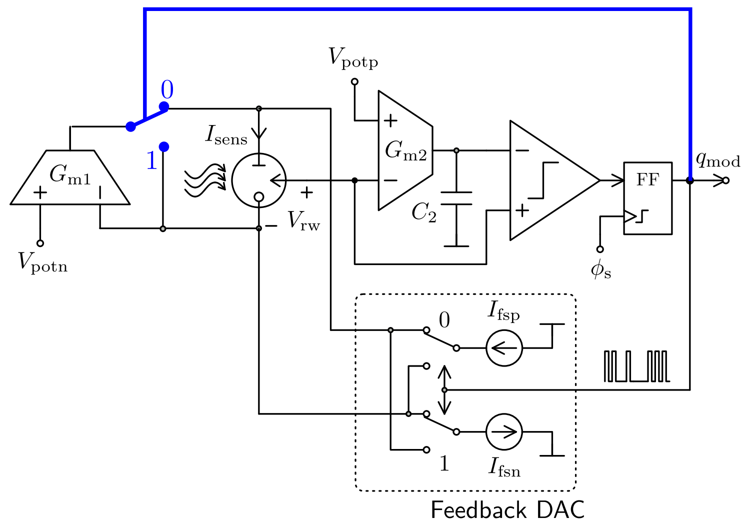
$$G_{\mathrm{mf1}} \equiv G_{\mathrm{mf2}} \doteq G_{\mathrm{mf}}$$

$$L_3(s) \doteq L_1(s) = -R_{\mathrm{ct}} G_{\mathrm{mf}} \frac{1+\tau_2 s}{(1+\tau_1 s)\,\tau_2 s}$$

  - Gm1 only has to cope with Ifsp,n mismatching.

Flicker Noise Cancellation

- Gm_1 OTA **switching.**
- $\text{I}_{\text{fsp,n}}$ noise currents are always **bypassed** to Gm_1 OTA or **biphasically** integrated into Vrw.



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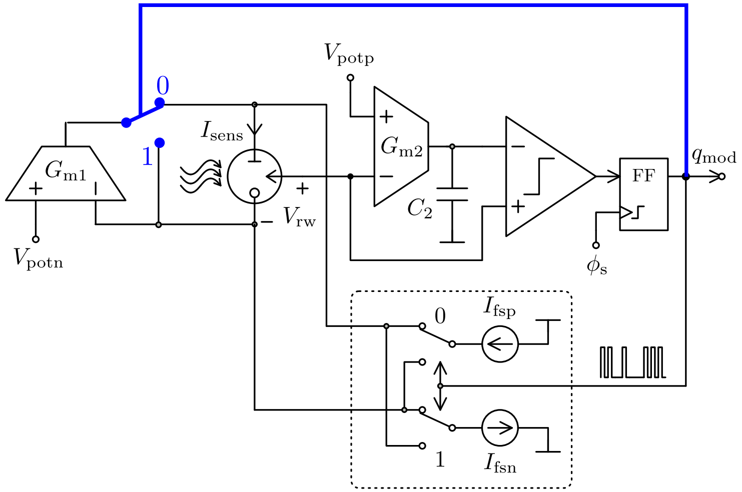
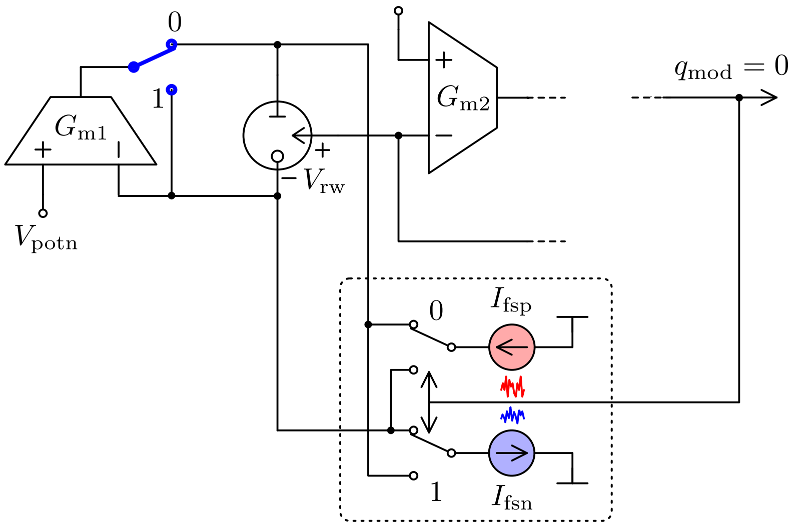


- **qmod = 0**



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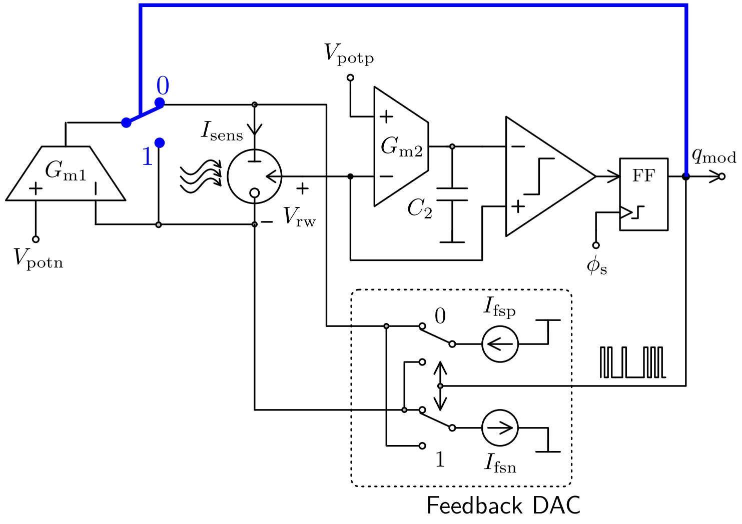

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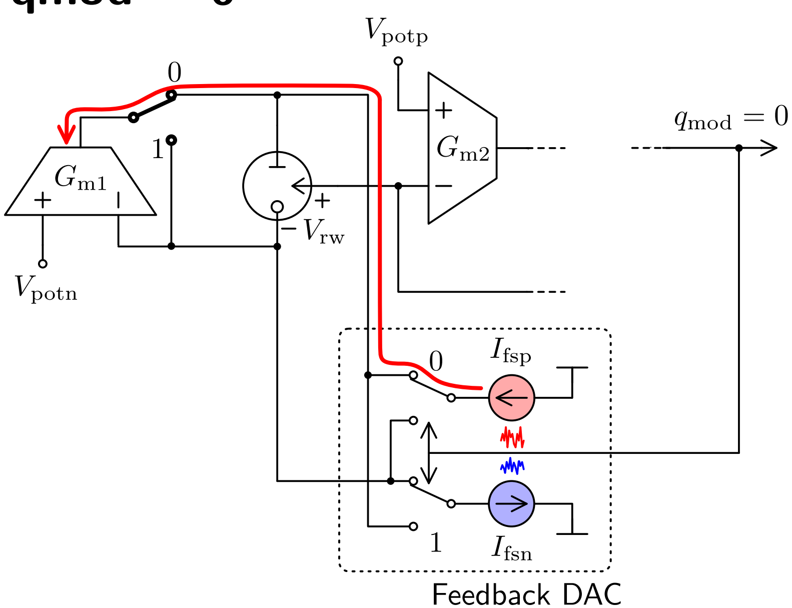

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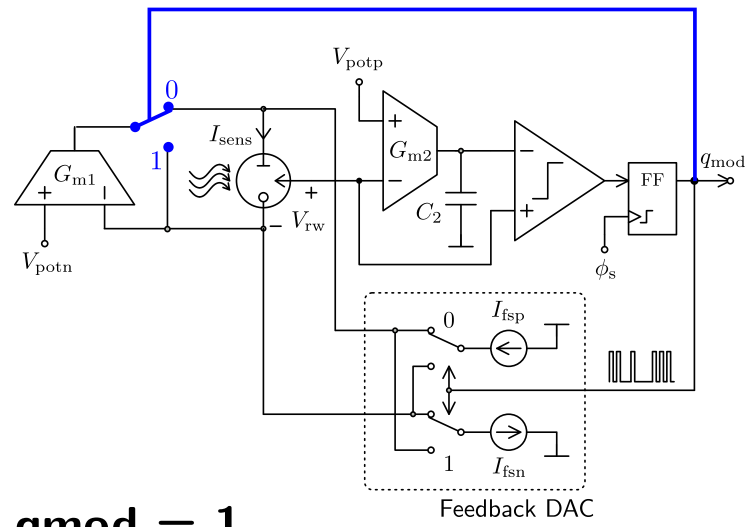

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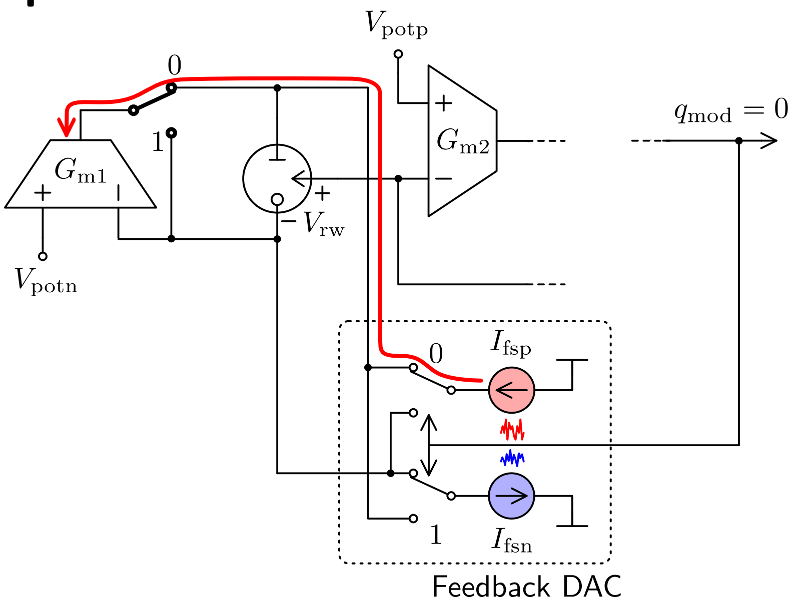

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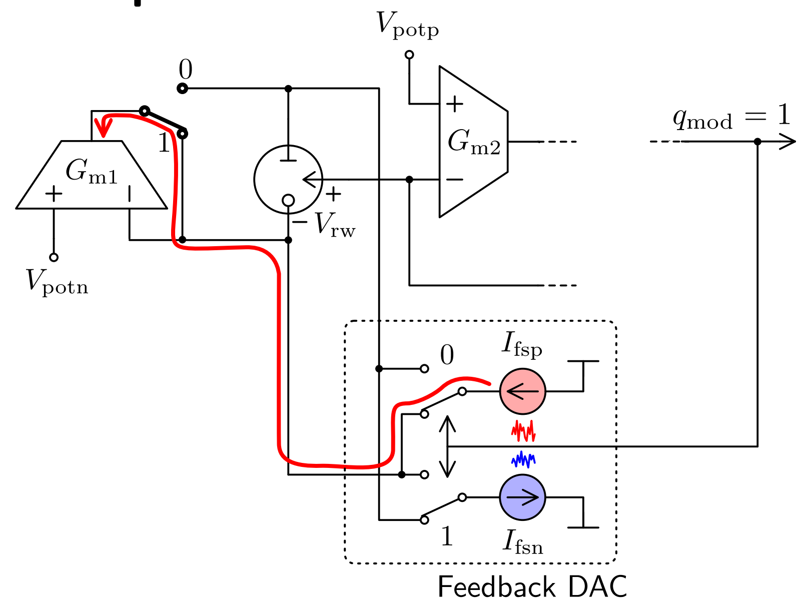

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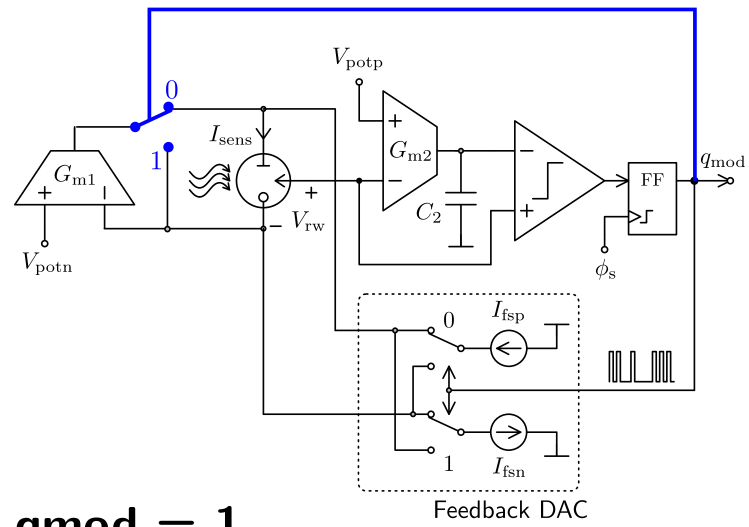
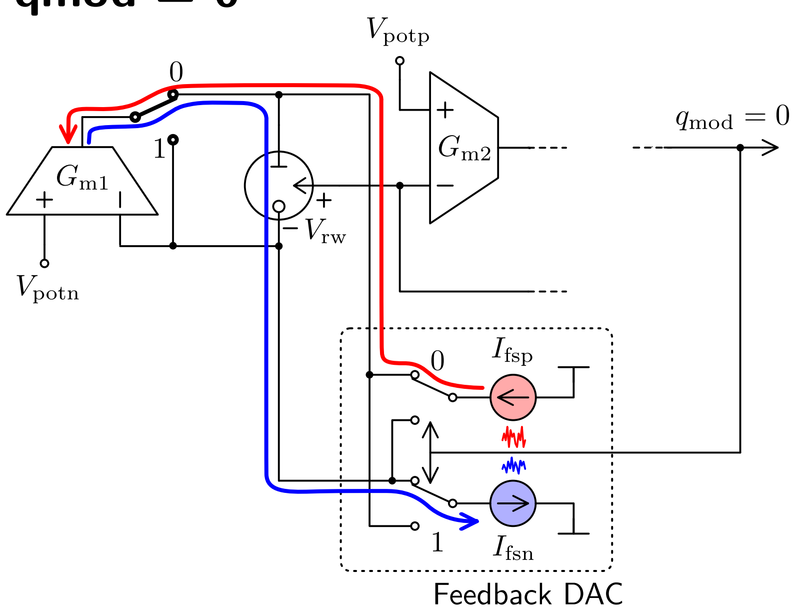


- **qmod = 0**



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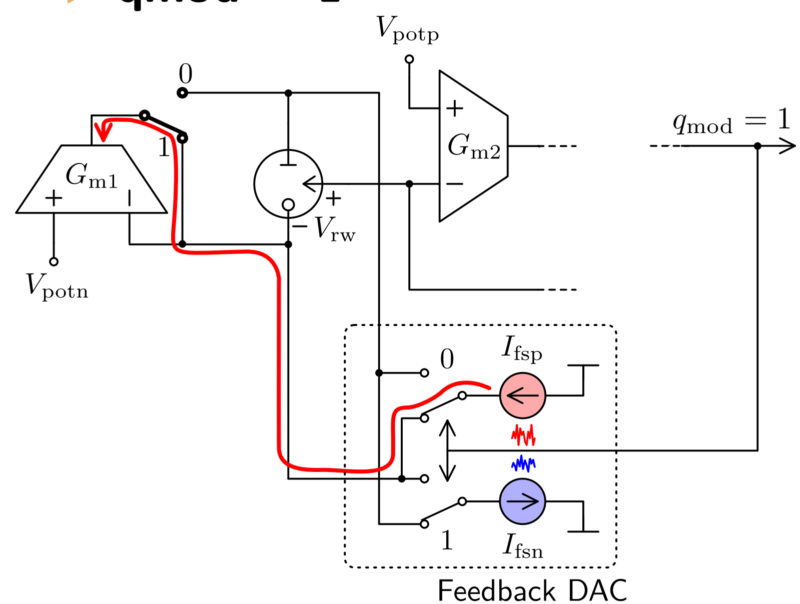

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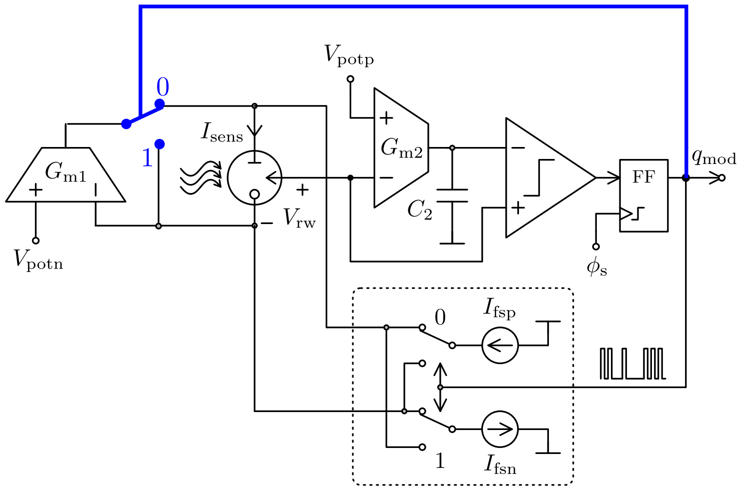

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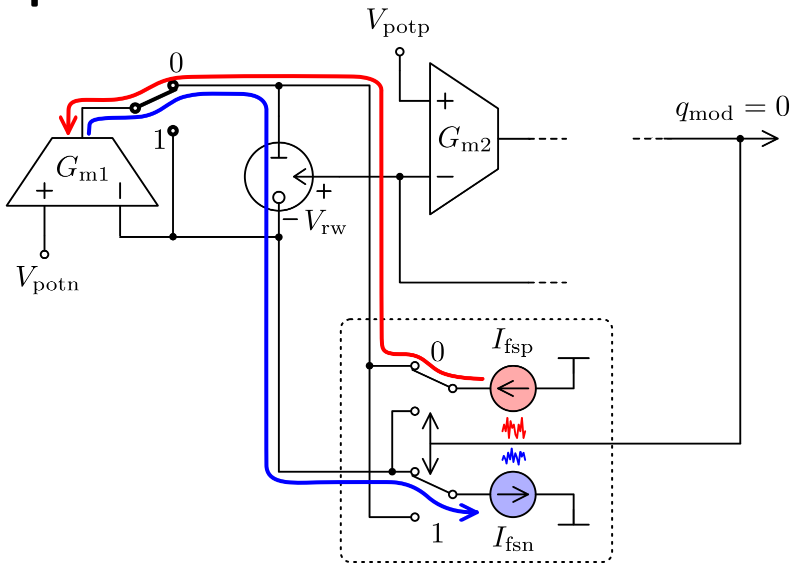

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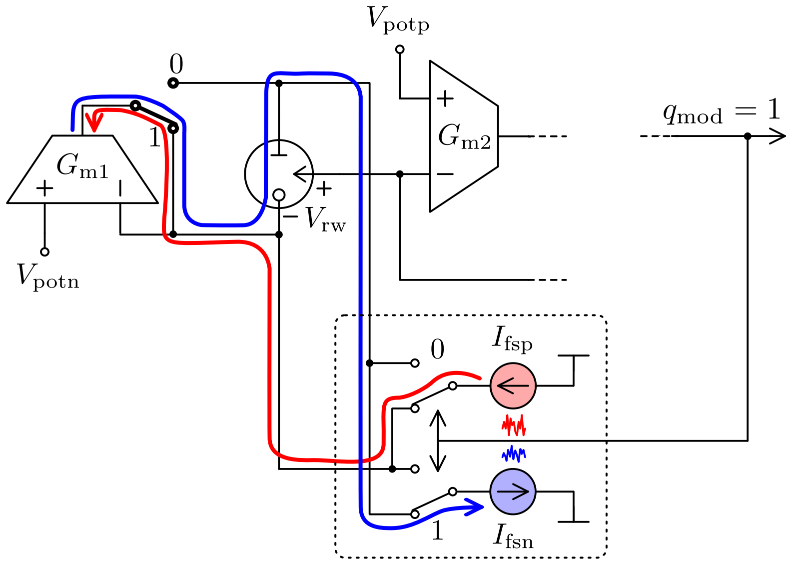
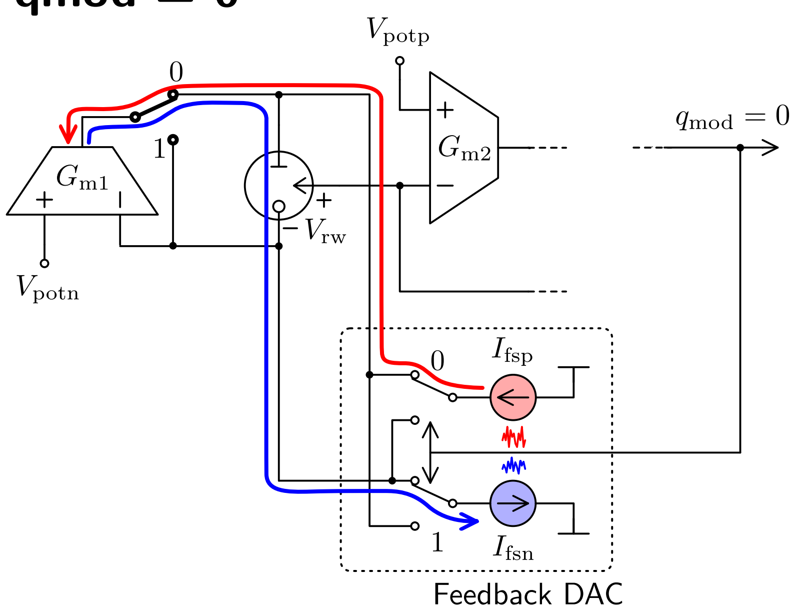


Flicker Noise Cancellation

- Optimum cancellation when **qmod** has **equal** probability of **1's** and **0's** quant. symbols (case of **very weak chemical signals**).

- **qmod = 0**



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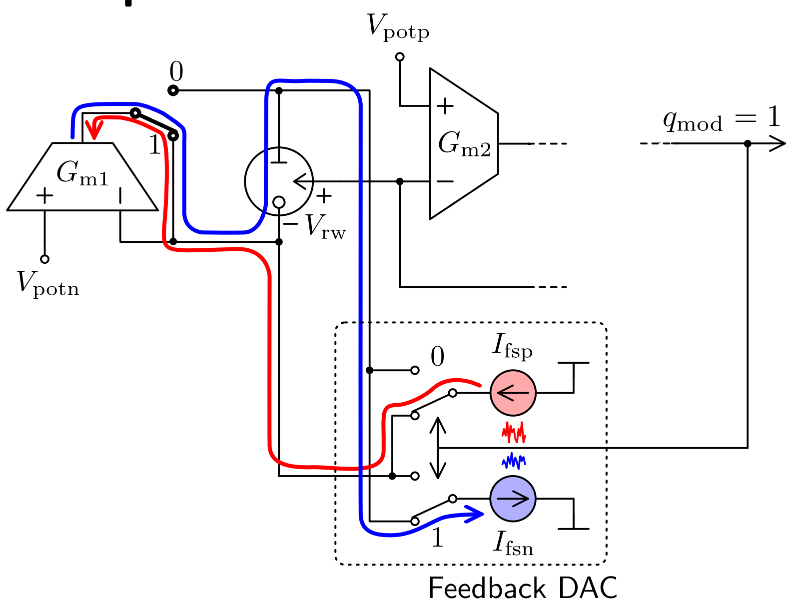

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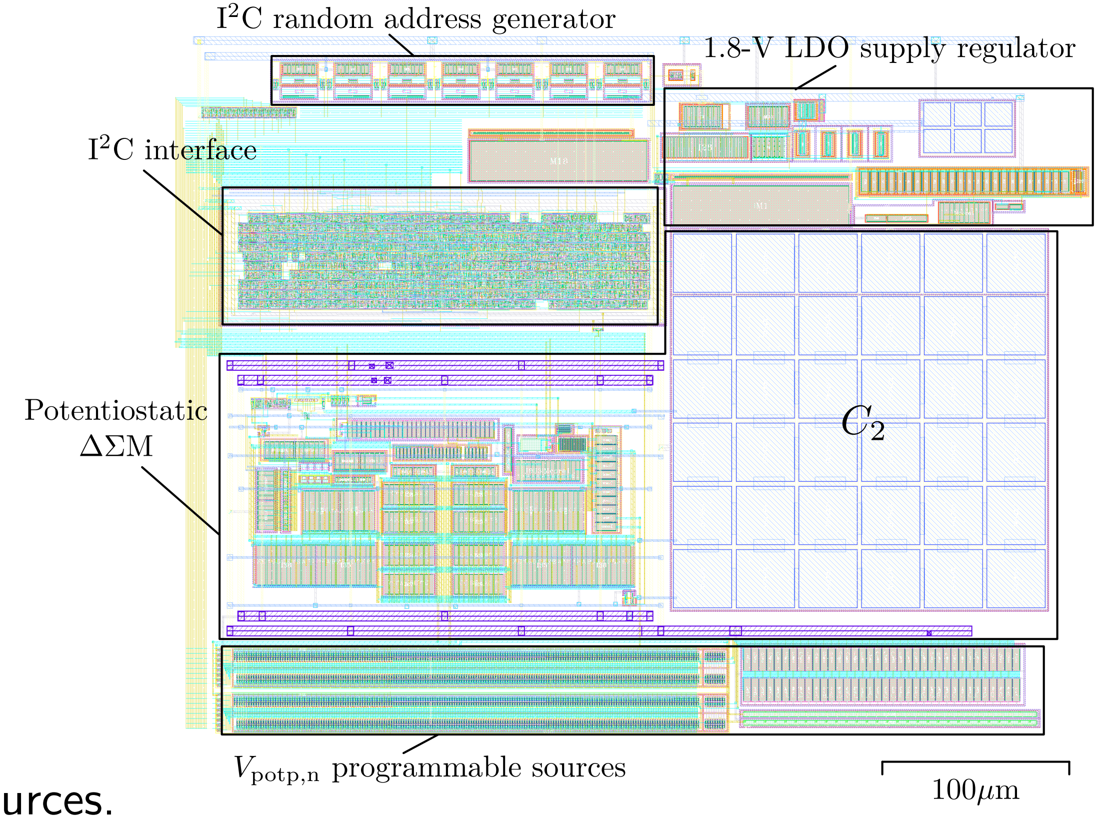
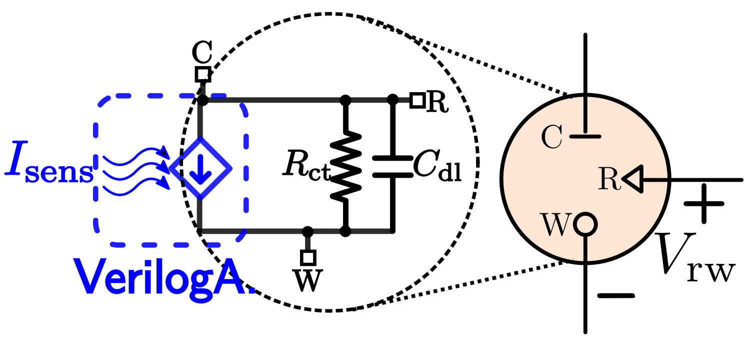
Electrochemical sensor frontend CMOS layout

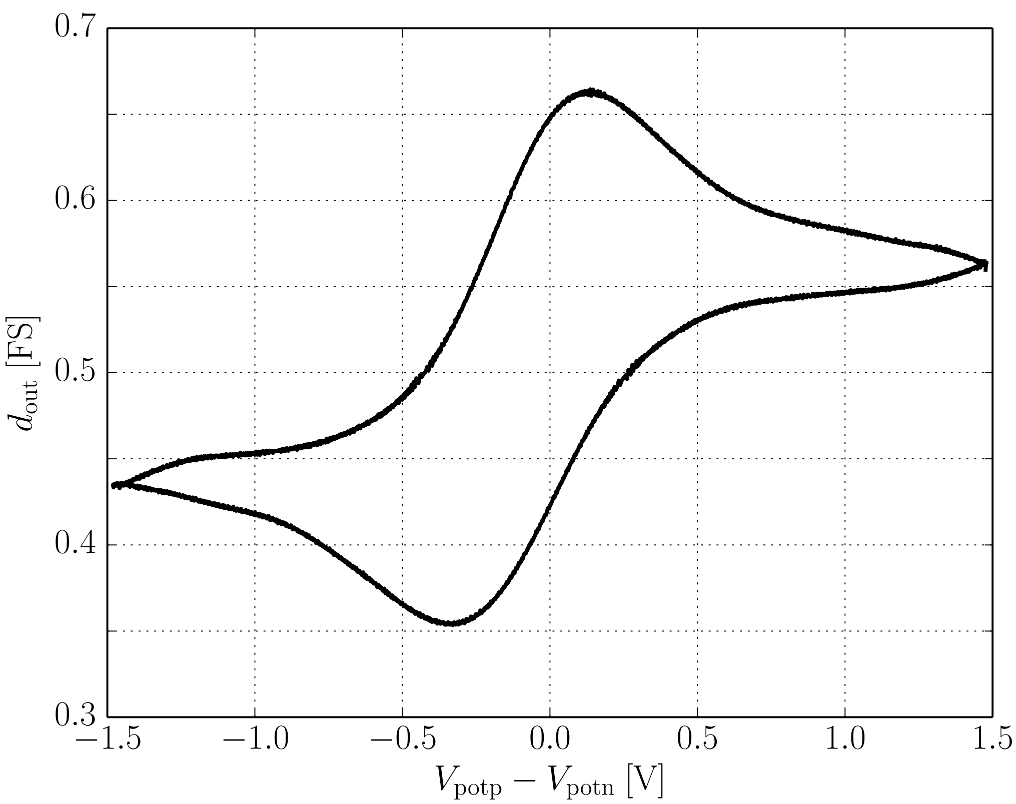
- **0.18µm** 1P6M CMOS X-FAB technology (XH018).
- 480µm x 370µm (**0.18mm²**).
- On-Chip auxiliary modules.
  - **I²C** 4-wire bus interface.
  - **1.8-V capless LDO** core supply regulator.
  - **Current** generator.
  - **Vpotp,n** programmable sources.



Post-Layout Simulations

- **3-Vpp** cyclic voltammetry example under **1.8-V voltage supply.**
- **VerilogA:** Vrw-Isens DC look-up table based on a Cyclic Voltammetry.
- Third order Butterworth low-pass filter as digital decimator. 2.5-Hz cutt-off freq.

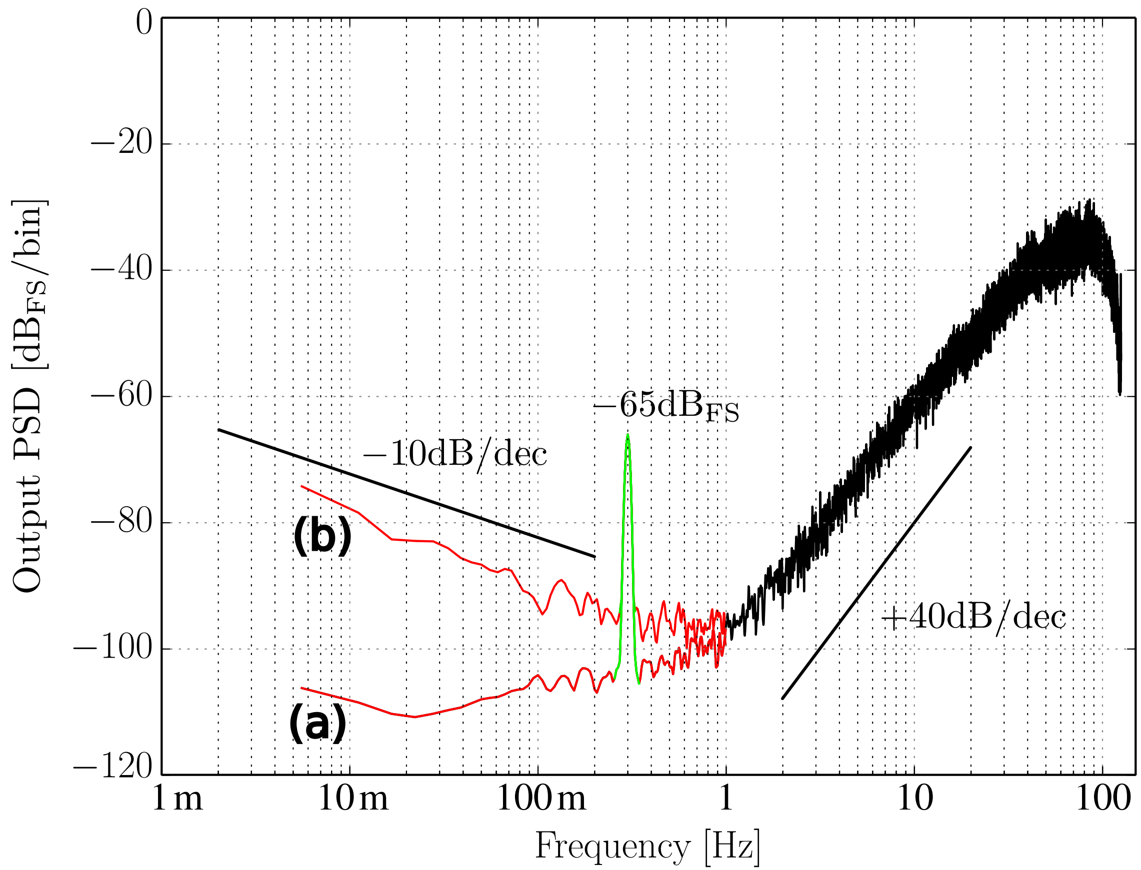




Post-Layout Simulations

- **Output spectrum** comparison w/**(a)** and w/o**(b)** flicker cancelation technique.

- Weak input signal **-65dB$_{FS}$**
- **±100-nA** full scale.
- **Oversampling ratio** 128:
  - **Sampling freq.** 256Hz
  - **Bandwidth** 1Hz



Performance simulation results

Parameter		Value	Units
Input	**max. full scale**	**±900**	**nA**
	full-scale prog.	**100**	**nA/step**
	bandwidth	1	Hz
Potentiostat	voltage range	±1.65	V
	voltage prog.	6.3	mV/step
	voltage ripple	<20	mV_{pp}
	voltage offset ($\pm\sigma$)	10	mV_{rms}
ADC	$SNDR_{max}$ FS =±100nA	70	dB
	±900nA	72	
	composite DR	**90**	**dB**
	oversampling ratio	128	
Power	supply voltage	1.8	V
	core consumption	**72**	μW_{rms}
Silicon area		0.18	mm^2

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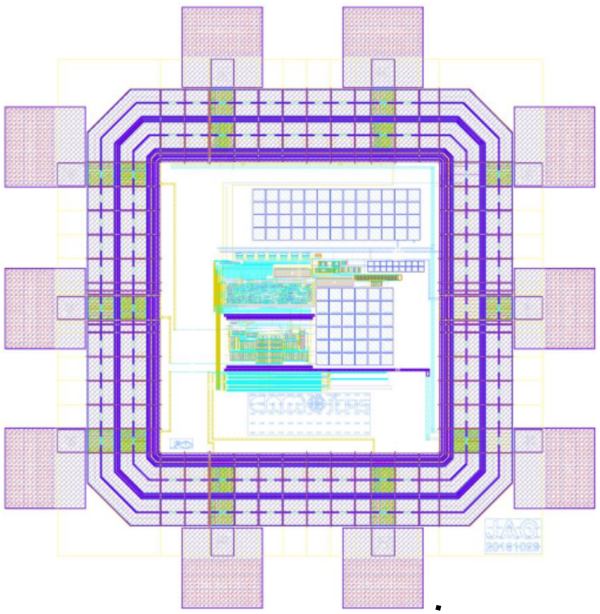
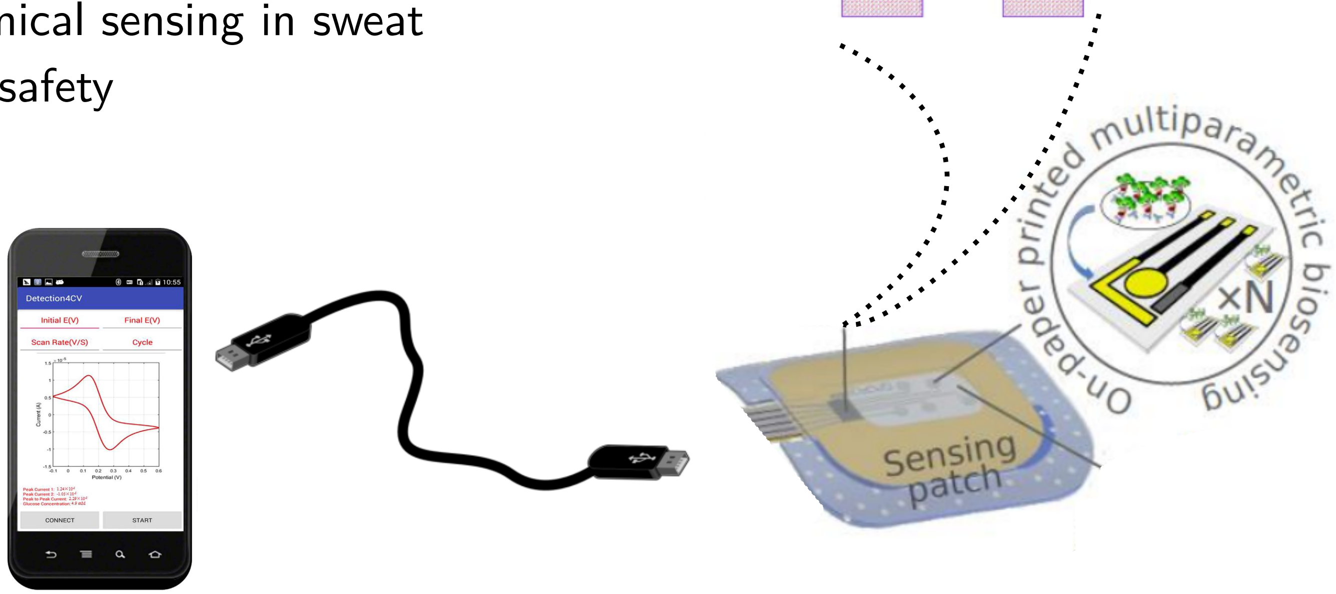
- **Compact architecture (0.18mm^2)** thanks to the electrode-electrolyte interface used as an integrator stage in the $\Sigma\Delta$M structure.
- **Wide range (±1.5V)** potentiostat programmability with **minimalist** analog circuits fully integrable in purely digital CMOS technologies.
- Improved **dynamic range (90dB)** thanks to Feedback DAC **flicker noise cancellation** mechanism.
- **High resolution** with sub kHz-range sampling frequencies **(256Hz)**.

Applications and benefits

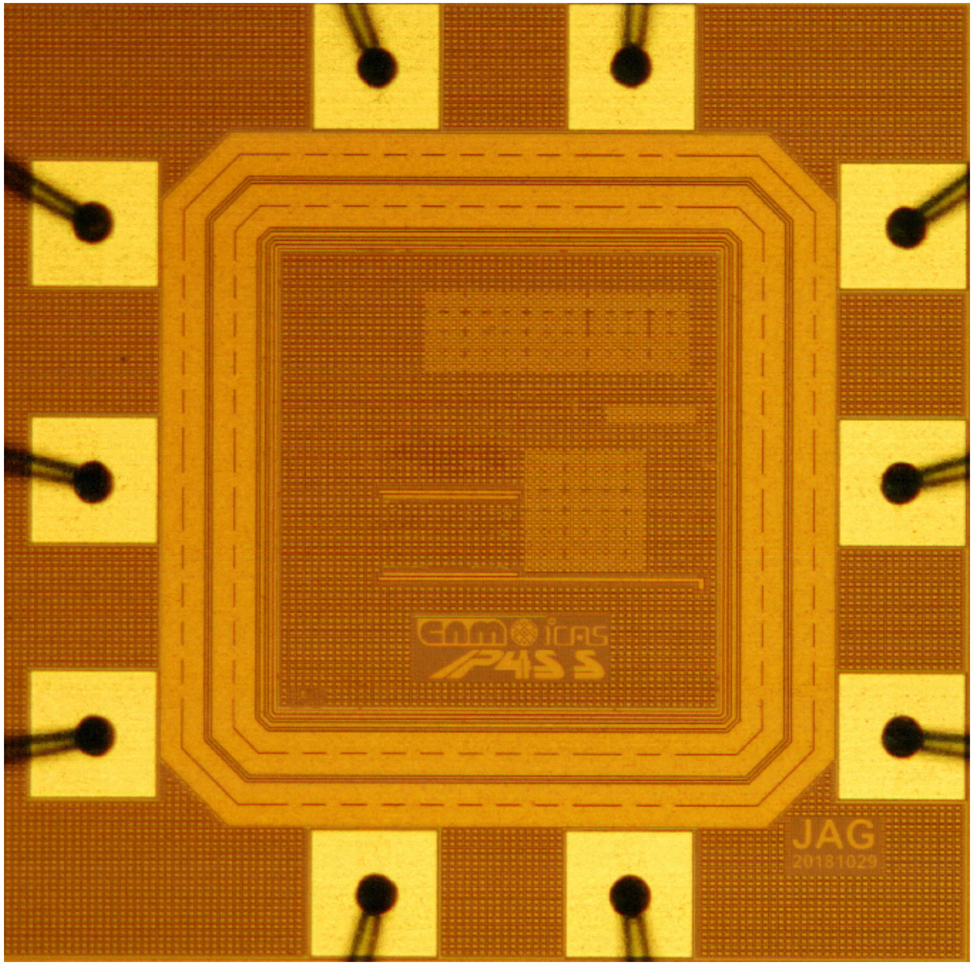
- **I^{2}C** plug & play (power and comm.)
- 200µm x 200µm pads
- First trials of ASIC **flip-chip** on screen-printed flexible substrates
- Wearable for chemical sensing in sweat
- Food quality and safety





- Currently being measured...

Thanks for your attention!



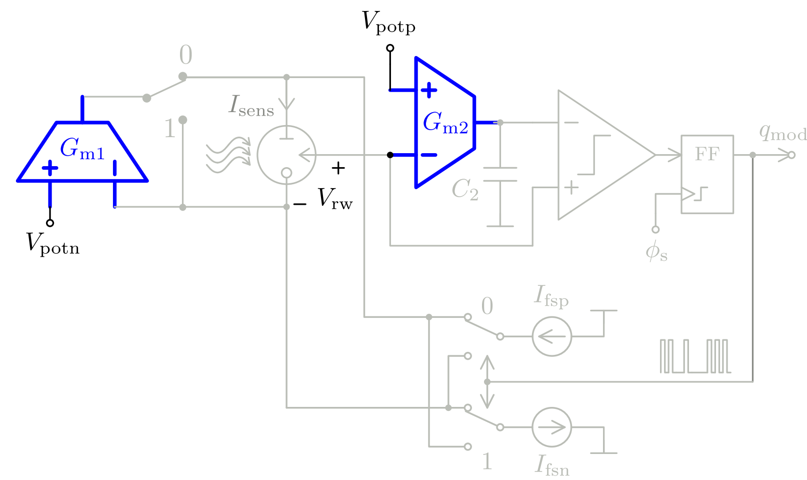
Comparison of CMOS Potentiostatic FRONTENDS

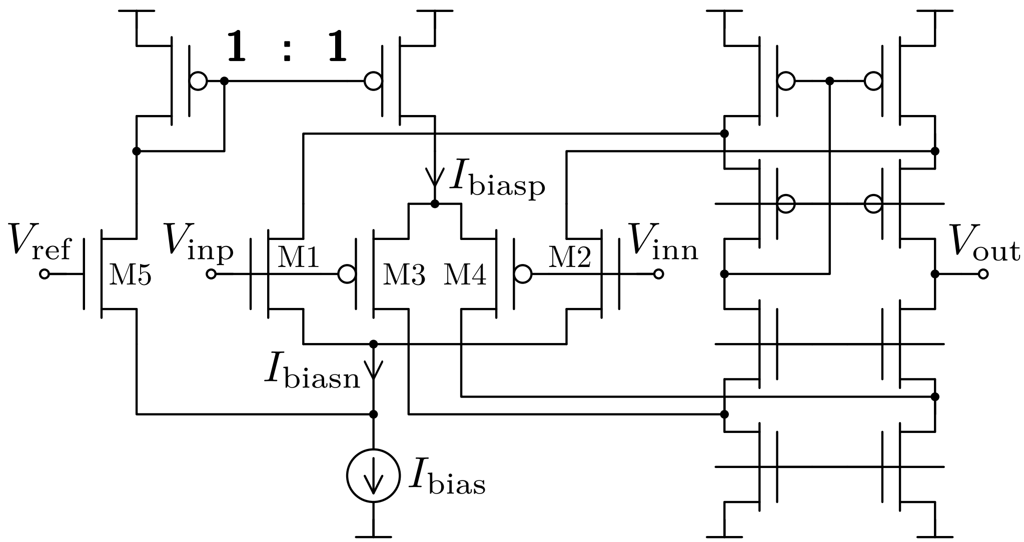
	This work	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	
ADC architecture	SI CT ΔΣM	Analog output	Dual Slope	Dual IAF/ off-chip	SC CT ΔΣM	SI CT ΔΣM	
Technology	180	180	250	180	600	2500	nm
Supply	1.8	1.8	2.5	1.8	5	5	V
Pot. range	3	3.2	1.25	0	4	3	V_{pp}
Full scale	±0.1 to ±0.9		±0.25	±11.6	±0.1	+2 to +32	μA
Bandwidth	1	500	2500	100	10	2	Hz
$SNDR_{max}$	70 @0.1nA 72 @0.9nA	63	54	< 50*	68	71	dB
DR	90	63	56	155	68	71	dB
Power	72	15800	>10000	5220*	1040	25	μW
Area	0.18		0.9	0.09	0.03	6.4	mm^2

*without including off-chip ADC.

Low-power rail-to-rail CMOS circuits

- **Wide** Vrw programmability imposes wide **input/output common-mode range** for **Gm$_1$** and **Gm$_2$**.

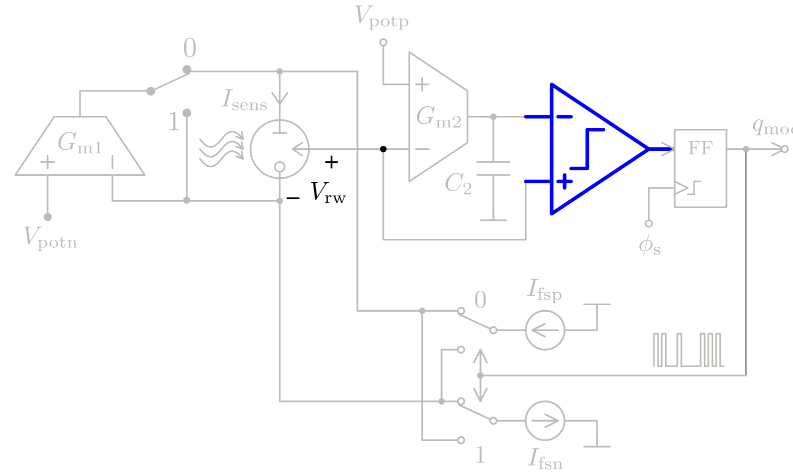


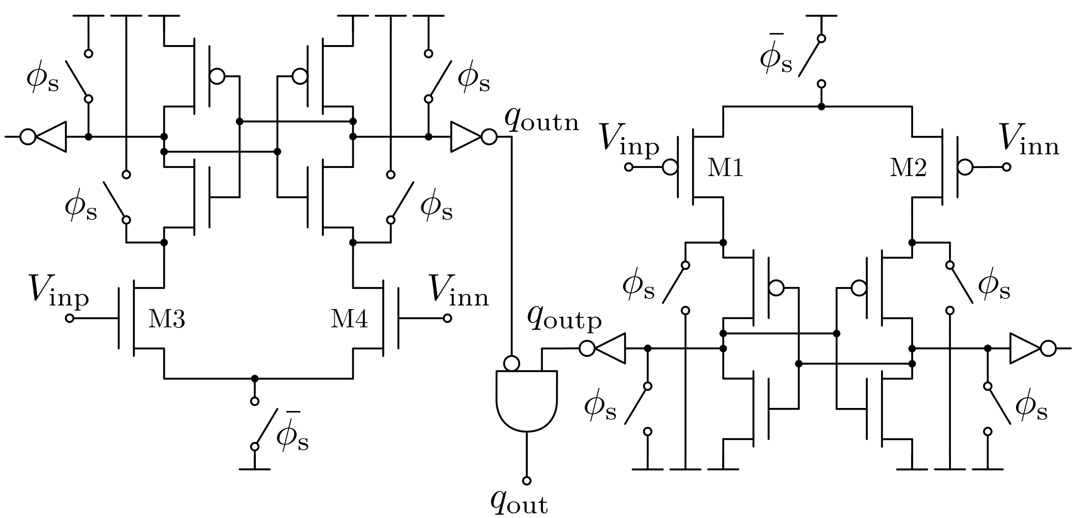


- Constant gm over the input common-mode voltage:
  - **M1-M4** in **weak inversion**
  - Sum of tail currents **I$_{\text{biasp,n}}$** constant

Low-power rail-to-rail CMOS circuits

- **Wide** Vrw programmability imposes challenging **input common-mode range** for the **quantizer.**





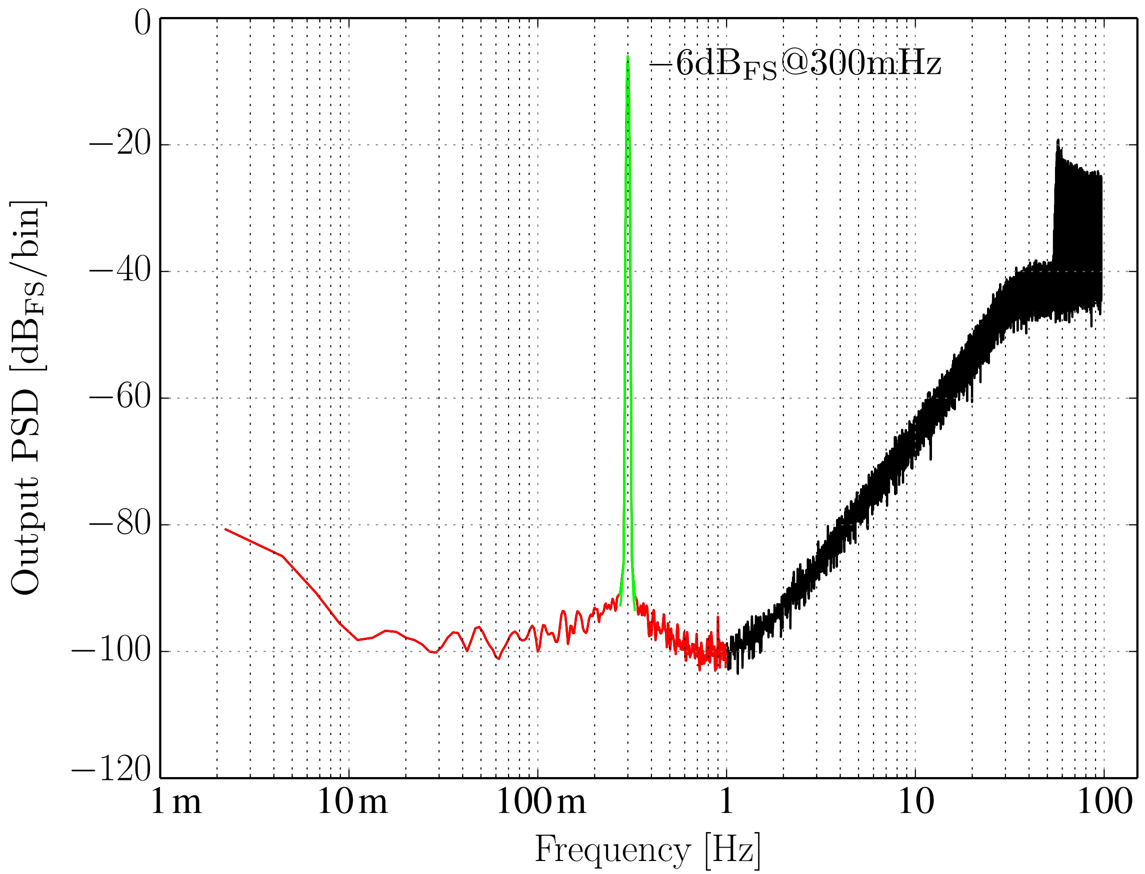
$(V_{inp}+V_{inn})/2$	q_{outp}	q_{outn}	q_{out}
close to V_{DD}	1	$\text{sign}(V_{inn}-V_{inp})$	$\bar{q}_{outn}$
otherwise	$\text{sign}(V_{inp}-V_{inn})$	$\text{sign}(V_{inn}-V_{inp})$	$q_{outp}\cdot\bar{q}_{outn}$
close to V_{SS}	$\text{sign}(V_{inp}-V_{inn})$	0	q_{outp}

- Complementary latched comparators:
  - **$q_{outp,n}$ digitally combined,** giving priority to the one still being operational.
  - Zero-static power consumption

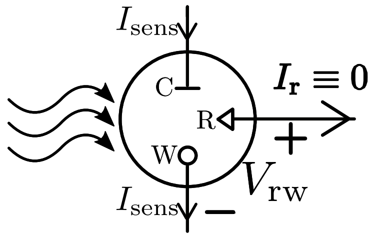
Post-Layout Simulations

- **Output spectrum** for half full-scale input signal **-6dBFS.**

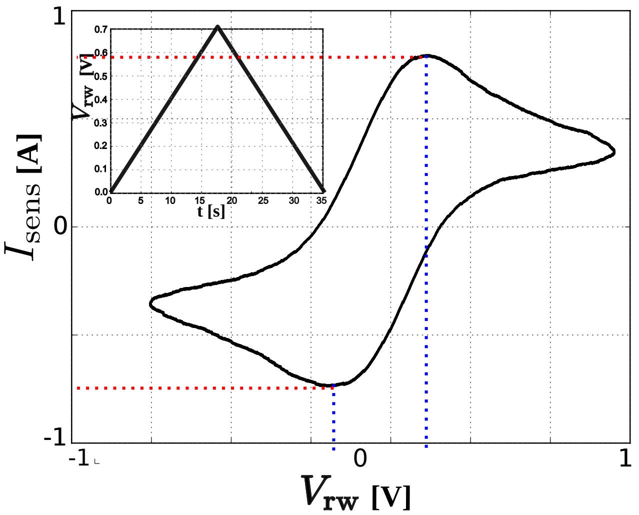
- **±100-nA** full scale.
- **Oversampling ratio** 128:
  - **Sampling freq.** 256Hz
  - **Bandwidth** 1Hz
- **SNDRmax**
  - **70-dB @** ±100nA FS
  - **72-dB @** ±900nA FS



Amperometric Electrochemical Sensors



- Different **detection methods** are required:
  - **Cyclic Voltammetry:**
    - Most widely used electrochemical technique.
    - Rapid location of the redox potentials.
    - Wide sweeping potentials



  - **Chronoamperometry:**
    - Vrw stepped and Isens monitored as a function of time.